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Department of the Navy
BUREAU OF YARDS AND DOCKS
Contract NOy-12561

FINAL REPORT

John H. Carr

Hydrodynamics Laboratory
Hydraulic Structures Division
CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California

Report No. E-11.4
November, 1954

Project Supervisor:
John H. Carr

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CONTENTS

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I. INTRODUCTION

Contract NOy-12561 was initiated 28 June 1945 for the purpose of conducting hydraulic model experiments to guide the extensive harbor improvements then in process and planned for, at Apra Harbor, Guam, M. I. The contract was continued through change orders and finally terminated on 30 November 1954. The Apra Harbor investigation was completed at the end of 1948, and during the following contract period activity was directed along the lines of basic investigations of wave phenomena as they affect harbors and harbor structures.

The program of the Laboratory was formulated and directed by Robert T. Knapp, Professor of Hydraulics, during the Apra Harbor studies and those immediately following. During this time laboratory facilities were designed and procured and the general program, which was followed by the project until its completion, was delineated. Dr. Warren O. Wagner was supervisor of the project during most of the Apra Harbor study. From the spring of 1949 until the termination of the contract, the project was supervised by Mr. John H. Carr.

In the following sections of this report, the aim and procedure of the several investigations are outlined, and the principal results summarized.

II. APRA HARBOR MODEL STUDIES

A. Scope of Investigation

The Apra Harbor study considered three main phases of the harbor improvement project:

(1) Outer breakwater location

(2) Evaluation of inner harbor improvements

(3) Determination of circulation within the harbor

The outer breakwater study included the laboratory evaluation of eight breakwater plans, ranging from the unimproved reef to complete breakwaters of differing alignments and elevations. Detailed studies were made also of six breakwater termini configurations.

The evaluation of inner harbor improvements included the study of 59 different shoal and inner breakwater configurations, the investigation of long-period surging in the harbor and a study of alternate harbor entrances.

The study of harbor water circulation included the effects of waves and ocean currents, and of tide-induced flows through artificial venting channels.

B. Apparatus and Techniques

Two facilities were utilized in the Apra Harbor Study, the outdoor model basin of the Hydraulic Structures Laboratory on the main campus of the California Institute of Technology and a new enclosed laboratory constructed at Azusa, California. The campus model basin is approximately 40-ft square and was equipped with such auxiliary equipment as a plunger-type wave generator, current pump, camera boom and water storage and distribution systems. The Azusa Laboratory building is a modified Army Advance Base hangar with floor space 148 feet by 162 feet and over-all height of 47 feet. The building modifications include: lower tier of sheet metal covering replaced with corrugated glass, concrete slab floor, underground water storage tanks, and a two-story shop and office annex.

Several methods of topographic model construction were investigated, the most successful being used for the construction of the large (1:360) undistorted model at the Azusa Laboratory. This method involved the construction of cast concrete sections, 4' x 4', with the topography rendered in 1/2" (15') increments by the use of plywood mold templatescut along the contour lines. The blocks were grouted at proper elevation to the model base structure and the contours then faired in with plaster.

Pneumatic wave machines were developed for the Azusa Laboratory. These machines consisted of a sheet metal tank chamber and nozzle assemblies 20 feet in length,on which blower and valve mechanisms were mounted. The blowers were powered by two-pole synchronous motors, to which variable frequency electric power was supplied by a variable speed alternator. This arrangement permitted synchronized speed control of all wave machine blowers over a wide speed range. The valve mechanisms which controlled the variation of wave machine chamber pressure were cam-driven by selsyn motors. All selsyn motors were driven from a common selsyn generator equipped for wide-range speed control, thus providing exact synchronization of all wave machines at any desired wave period.

Wave height measuring equipment was developed in the form of electric current conductivity elements. Rectifying and filtering circuits made possible the recording of 16 wave height records on a 6-in. record with galvanometer oscillograph. For the evaluation of harbor wave disturbances, 16 wave height measuring elements were used in an array on 4" centers in order to obtain a representative space-average record.

Photographic techniques were extensively used in the study. Large-size electronic flash lamp units were provided to illuminate the model, and photographs were taken with modified K-17 aerial cameras from a camera platform and tower, 32 and 50 ft above the model to obtain qualitative records of wave patterns and disturbance levels. Measurements of currents and harbor circulation were made by multiple exposure photographs of drifting reflector floats.

C. Summary of Results

The alignment of the outer breakwater was found to be so restricted by the topography of reefs and banks that there was very little opportunity to control harbor wave disturbance by choice of breakwater alignment.

However, it was demonstrated that considerable protection from overtopping and damage could be afforded the breakwater by following an alignment on the harbor side of the outer bank.

Wave disturbance levels in the breakwater-protected outer harbor were measured and active and calm areas so determined to guide future harbor improvements.

The protection afforded to the repair basin and inner harbor areas by the existing group of shoals was found to be very good. Various breakwater structures proposed to supplement or replace these shoals were found to provide but a relatively small measure of increased protection.

Water circulation within the harbor was found to be mainly due to wave action. Extremely low current velocities were found in the inner harbor and repair basin areas, indicative of a potentially serious pollution problem in these areas. The provision of a tidal venting channel connecting the inner harbor and the ocean was found to greatly alleviate this condition.

D. References

Progress and results of the Apra Harbor study were reported in a series of 32 monthly progress reports and a final report. The final report, "Model Studies of Apra Harbor", Hydrodynamics Laboratory, Report No, N-63, June 1949, prepared under the direction of Professor Robert T. Knapp, covers in detail all phases of the work, hence detailed reference to the progress reports is omitted from this summary.

The following publications drew in part upon the results of the Apra Harbor Study:

1. Carr, J.H., "Long-Period Waves or Surges in Harbors", ASCE Proc. - Separate No. 123, April, 1952
2. Vanoni, V.A., and J.H. Carr, "Harbor Surging", Proceedings of the First Conference on Coastal Engineering, 1951.
3. "Model Studies of Apra Harbour". A review by R.R. Minikin. The Dock and Harbour Authority. In six issues: Vol. 31, No. 366, April 1951, pp. 367-371; Vol. 32, No. 367, May 1951, pp. 9-14; Vol. 32, No. 368, June 1951, pp. 60-64; Vol. 32, No. 369, July 1951, pp. 81-86; Vol. 32, No. 370, August 1951, pp. 125-129; Vol. 32, No. 370, September 1951, pp. 155-159.

III. MOBILE BREAKWATER STUDIES

A. Scope of Investigation

The investigation of mobile breakwaters had as its original aim the evaluation of the pneumatic or air-bubble breakwater. This work was expanded to include the study of water currents and periodic arrays of partially reflecting structures. Later, attention was directed towards the wave reflecting capabilities of trapped masses of water, and towards practical means for obtaining such entrapment. One such development, rigidly spaced floating vertical bulkheads, was considered of sufficient promise to warrant the filing by the Government of a patent application.

B. Apparatus and Techniques

The investigations of mobile breakwaters were conducted on a two-dimensional basis in wave channels, the various structures or breakwater environments completely spanning the channel and therefore representing a typical section of a three-dimensional situation.

Measurements, which were mainly of wave height, made use of previously developed electrical and photographic techniques. Since most of the devices investigated produced appreciable wave reflection, special techniques were developed to permit the measurement of the separate incident and reflected components of a mixed wave system.

In addition to the experimental programs, some mathematical analysis of various breakwater systems was performed by both consultants and project staff members.

C. Summary of Results

The effectiveness of a pneumatic breakwater was found to be due to the horizontal water currents generated by the bubble stream. The magnitude of current required to prevent wave transmission was found to increase so rapidly with decreasing depth-to-wave length ratio that any type of water current breakwater device is only practical for deep-water wave condition ($\frac{d}{L} > \frac{1}{2}$). Periodically spaced structures were found to be effective in decreasing the transmission of waves, but also were found to be so critical with regard to wave period as to be highly impractical for prototype conditions.

The performance of trapped water mass barriers was found to closely approximate theoretical considerations. Various practical means for approximating the condition of a trapped water mass were demonstrated.

D. References

The first phase of the mobile breakwater study was reported in a series of four progress reports, two consultant-prepared reports and a final report. The final report covers all the material in the progress reports, which will therefore not be included in the following listing.

Later work on the water-mass aspects of the mobile breakwater problem are reported in four Interim Reports of the Laboratory, as listed below:

1. Schiff, L.I., "Gravitational Waves in a Shallow Compressible Liquid", Report No. N-64, Hydrodynamics Laboratory, California Institute of Technology, 1949.

2. Schiff, L.I., "Air Bubble Breakwater", Report No. N-64.1, Hydrodynamics Laboratory, California Institute of Technology, 1949.

3. Carr, J.H., "Mobile Breakwater Studies", Report No. N-64.2, Hydrodynamics Laboratory, California Institute of Technology, 1950.

4. Carr, J.H., J.J. Healy and M.E. Stelzriede, Progress Report July 1950,"Reflection and Transmission of Water Waves by Floating and Fixed Rigid Surface Barriers", Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology.

5. Carr, J.H. and M.E. Stelzriede, Interim Report July 1951, Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology (Floating surface barrier experiments).

6. Stelzriede, M.E., Interim Report, October 1951, Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology (Spaced bulkhead experiments).

7. Stelzriede, M.E. and J.H. Carr, Interim Report, December 1951, Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology (Spaced bulkhead experiments and theory).

The following publication drew in part upon the results of the Mobile Breakwater Study:

Carr, J.H., "Mobile Breakwater", Proc. of Second Conference on Coastal Engineering, 1952.

IV. HARBOR DESIGN STUDIES

A. Scope of Studies

The harbor design study was initiated as a detailed study of wave diffraction through a breakwater gap. In the next phase, the combined effects of wave diffraction and wave reflection from harbor boundaries were considered in relation to the wave disturbances in harbors of geometrically simple shapes. Finally, the information gained from the laboratory program was combined with other available material on wave processes to prepare a manual to guide the wave protection aspects of harbor design.

B. Apparatus and Techniques

The investigation of wave diffraction was guided by the Morse-Rubenstein theory of this process. An analytical study was made to adapt this theory to the water wave problem, and arrangements were made for the numerical computation of several cases of practical interest in harbor design by the Institute for Numerical Analysis of the National Bureau of Standards. Experiments were conducted to verify the theoretical results and to investigate some situations not amenable to analysis. These experiments were conducted in a basin which included an inshore area 24 ft x 32 ft with 3-in. water depth, and an offshore area 37 ft x 20 ft, with depth sloping from 3 in. to 12 in. One of the Apra Harbor wave machines was installed at the deep end of the basin, and breakwaters and gravel damping beaches in the shallow end. Wave height measurements in the lee of the breakwaters were made with conductivity elements at a fixed radius of 5.76 wave lengths from the center of the opening to obtain data on the angular distribution of energy resulting from diffraction through the breakwater opening.

Laboratory investigations of combined diffraction and reflection within a harbor were conducted in a basin approximately 42 ft x 90 ft, with water depth of 4 in. A pneumatic wave machine was constructed to operate in this water depth. Tests were made with a square, a rectangular and a trapezoidal basin, with various breakwater openings and absorbing beaches. Disturbances were measured with an array of wave height elements to obtain space-time averages in selected locations. A graphical method of combining reflection and diffraction was developed in the course of this study.

C. Summary of Results

Computations of wave energy distribution in the lee of a breakwater gap were made for gap lengths of 1/2, 1, 2, and 3 wave lengths and wave approach angles of 0°, 15°, 30°, 45°, 60°, 75°, and 90°, based on the Morse-Rubenstein theory. Experimental verification of these results were obtained for a large number of the cases. Some additional experimental data were obtained for converging and right-angle breakwater configurations.

A simple graphical method for determining the combined effects of diffraction and reflection on wave disturbance within a harbor of simple shape was developed and verified by model experiments.

The results of these studies were combined in the form of a manual to guide the wave protection aspects of harbor design.

D. References

The results of the laboratory studies were reported in a series of seven progress reports and a manual as follows:

1. Carr, J.H., Progress Report for June 1-December 31, 1949. Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology (Apparatus and procedure).

2. Carr, J.H., Progress Report for Jan. 1-June 30, 1950. Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology (Procedures and preliminary results).

3. Stelzriede, M.E., Theoretical Studies, June 1950. Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology (Summary of diffraction theories).

4. Carr, J.H., M. Meisels, and M.C. Walker, Progress Report for Aug. 1-Oct. 31, 1950, Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology (Summary of diffraction experiments).

5. Carr, J.H., J.G. Elliott, M. Meisels, and M.E. Stelzriede, Interim Report, Jan.-July 1952. Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology (Summary of diffraction computation program).

6. Elliott, J.G., J.C. Hufft and M. Meisels, Interim Report December 1951. Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology (Experiments and analysis, square and rectangular harbors).

7. Carr, J.H., J.G. Elliott, M. Meisels and M.E. Stelzriede, Interim Report, Jan.-July 1952. Hydrodynamics Laboratory,

Hydraulic Structures Division, California Institute of Technology (Summary of harbor disturbance studies).

8. Hydraulic Structures Division, Hydrodynamics Laboratory, California Institute of Technology Report No. E-11, "Wave Protection Aspects of Harbor Design", August 1952.

The following publication drew in part upon the results of the harbor design study:

Carr, J.H., and M.E. Stelzriede, "Diffraction of Water Waves by Breakwaters", National Bureau of Standards Circular 521, November 28, 1952.

V. WAVE FORCE STUDIES

A. Scope of Investigation

The initial phase of the investigation of wave forces included analytical and experimental studies of the case of wave reflection from plane barriers inclined at various angles and a family of curved and stepped-face barriers representative of prototype structures. The second phase of the study was concerned with the case of wave breaking on plane barriers. The experimental program covered a wide range of wave parameters - heights and lengths - in order to obtain data applicable to most prototype conditions.

B. Apparatus and Techniques

Experiments were conducted on a two-dimensional basis in long wave channels, with water depth of two feet. A three-component wave force balance was constructed, using strain gage-type force sensing cells and galvanometer oscillograph recording. Strain gage-type pressure cells were also utilized during part of the program to obtain pressure distribution data.

Models of prototype barrier structures were constructed as aluminum castings.

C. Summary of Results

A simplified theory was developed to predict the forces and moments acting on a vertical plane barrier due to wave reflection. This theory, which includes a second order (double wave frequency) term not previously considered in wave force analyses, was verified by experiment. Experiments also indicated that the theory is reasonably accurate in many cases of barrier profiles other than plane.

The investigation of breaking wave forces resulted in a fair correlation between a definite portion of the wave force impulse and the momentum of the wave just prior to breaking as calculated from solitary wave theory. The experimental results are presented as plots of dimensionless ratios in terms of the forces, wave heights, wave periods and calculated wave momentum.

The experimental technique of recording complete force-time histories provided evidence that the maximum force of structural significance is a suddenly applied load of appreciable duration. The magnitude of this load component is a reasonably consistent function of wave and barrier parameters while the impulsive initial force transient is highly variable in this respect and contributes but a small portion of the total impulse.

D. References

1. Meisels, M. and M.E. Stelzriede, Interim Report, December 1952-Mar. 1953, Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology (Apparatus and techniques).

2. Elliott, J.G., M. Meisels, and M.E. Stelzriede, Interim Report November 1953, Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology (Preliminary results, stepped barrier).

3. Carr, J.H., "Wave Forces on Plane Barriers", Hydrodynamics Laboratory, Hydraulic Structures Division, Report No. E-11.1, California Institute of Technology, October 1953.

4. Carr, J.H., "Wave Forces on Curved and Stepped Barriers", Hydrodynamics Laboratory, Hydraulic Structures Division, Report No. E-11.2, California Institute of Technology, June 1954.

5. Carr, J.H., "Breaking Wave Forces on Plane Barriers", Hydrodynamics Laboratory, Hydraulic Structures Division, Report No. E-11.3, California Institute of Technology, November 1954.

VI. MISCELLANEOUS STUDIES

In addition to the work previously described a few programs were undertaken either at the request of the Officer in Charge of the Contract, or as laboratory explorations of possible future programs of investigations.

A. Mayport Model Study

This study was conducted at the request of the Officer in Charge, to obtain data on wave disturbances to be expected in berthing areas of the Mayport, Florida, Naval Station after certain harbor improvements were completed. A simplified model was constructed and measurements made in February 1951, and a more detailed model with scales of 1:240 horizontal and 1:120 vertical was constructed and tested during the last quarter of 1951. This work is described in an informal laboratory report:

Carr, J.H. and M. Meisels, Mayport Naval Station, Hydrodynamics Laboratory, Hydraulic Structures Division, California Institute of Technology, December 1951.

B. Stability of Caisson Breakwaters

In order to explore other aspects of the mobile breakwater problem, a preliminary study of stability and sand scour characteristics of "Phoenix-type" caissons was conducted. A movable-bed model basin approximately 25-ft square was constructed, and tests run with 1:60 scale models of Phoenix caissons. Several interesting observations of stability criteria were made and a photographic technique for recording scour was developed before this investigation had to be abandoned.

Apparatus and equipment are described in Ref. 7 of Section IV above, and a summary of the entire program is contained in the following informal report:

Elliott, J.G., "A Preliminary Investigation of the Stability of Caisson-Type Breakwaters", Hydrodynamics Laboratory Hydraulic Structures Division, California Institute of Technology, November 1952.

C. Measurements of Wave-Induced Velocities and Accelerations

As an adjunct to the wave force study, an investigation was made of precise methods of measuring water particle velocities and acceleration. A stroboscopic technique was developed which is much superior to the motion picture methods employed by other investigators. Measurements of velocity and acceleration at every part of the particle orbit were obtained with errors of the order of 1%.

This work is described in an informal report:

Elliott, J.G., Interim Report, July 1953, Hydrodynamics Laboratory Hydraulic Structures Division, California Institute of Technology.